B.S.T.J. BRIEF

All Terminal Bubbles Programs Yield the Elementary Symmetric Polynomials

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R. L. Graham has discussed various combinatorial aspects of the behavior of magnetic domains or "bubbles".[1] Representing the initial state of a configuration of n magnetic domains by the n-tuple of indeterminates $B = (X_1, \cdots, X_n)$, he showed that subsequent configurations of magnetic domains obtainable (within the constraints of the problem) correspond exactly to subsequent n-tuples of Boolean expressions in the X_i's* obtainable from B through an application to B of a product of transformations ("commands" in Ref. 1) of the form $T_{ij}(1 \leqq i < j \leqq n)$ where if $P = (P_1, \cdots, P_n)$ is an n-tuple of Boolean expressions in the X_i's, then $T_{ij}(P) = (Q_1, \cdots, Q_n)$,

$$Q_k = \begin{Bmatrix} P_i \bigcup P_j & \text{if} \quad k = i \\ P_i \bigcap P_j & \text{if} \quad k = j \\ P_k \quad \text{otherwise} & \end{Bmatrix}, \qquad k = 1, \cdots, n.$$

Furthermore, he showed that

$$\text{if } \mathfrak{I} \text{ is an } \tbinom{n}{2}\text{-fold product of such transformations and if } T \text{ is any other, then } (T \circ \mathfrak{I})(B) = \mathfrak{I}(B). \qquad (\dagger)$$

This provides a limitation on the number of distinct n-tuples of the form $\mathfrak{U}(B) = (P_1, \cdots, P_n)$ where $\mathfrak{U}$ is a product of transformations, and hence provides a limitation on the number of distinct P_i's thus obtainable from various $\mathfrak{U}$'s. Graham showed that for $n = 11$, this limitation implies that not all Boolean expressions in the X_i's are realizable as a P_i.

This led to an (as yet unsuccessful) attempt to characterize those expressions which are realizable. The purpose of this note is to observe a fragmentary result in this direction: that if $\mathfrak{I}$ is as above, then $\mathfrak{I}(B) =$

* A Boolean expression in the X_i's is either a term of the form X_i $(1 \leqq i \leqq n)$, a term of the form $P \cup Q$ or a term of the form $P \cap Q$, where both P and Q are Boolean expressions in the X_i's; expressions may be reduced as if the X_i's were sets.

$(S_1, \cdots, S_n)$ where S_i is the elementary symmetric polynomial in $X_1, \cdots, X_n$ of degree i (here interpreting $\cup$ as $+$ and $\cap$ as $\cdot$). The situation will be rephrased in terms of a semiring.

For a fixed n let R be the (Boolean) commutative semiring generated by $X_1, \cdots, X_n$ subject to the relations:

$$\text{for} \quad i = 1, \cdots, n, \quad (1)\ X_i^2 = X_i,$$
$$(2)\ fX_i + f = f \quad \text{for all} \quad f \in R.$$

It follows that $2X_i = X_i (i = 1, \cdots, n)$ and hence, each $f \in R$ is a Boolean polynomial in the indeterminates $X_1, \cdots, X_n$, (that is, the X_i's behave like sets with respect to $+$ and $\cdot$ interpreted as $\cup$ and $\cap$ respectively).

Throughout, if $x \in R^n$ (the set of n-tuples of elements of R), then for $1 \leqq k \leqq n$, x_k will denote the kth coordinate of x, that is, $x = (x_1, \cdots, x_k, \cdots, x_n)$. Let T (or T_n) be the set of transpositions of $\{1, \cdots, n\}$ and for $t \in T$—say $t = (i, j)$, $i < j$—define $t : R^n \rightarrow R^n$ by

$$(tf)_k = \begin{Bmatrix} f_i + f_j & \text{if} \quad k = i \\ f_i \cdot f_j & \text{if} \quad k = j \\ f_k & \text{otherwise} \end{Bmatrix}. \quad \text{Let } B = B_n = (X_1, \cdots, X_n) \in R^n$$

and set $\mathcal{C}_n = \bigcup_{k=0}^{m} T^k(B)$ where $m = \binom{n}{2}$* and $T^k = \{t_1 t_2 \cdots t_k \mid t_1, t_2, \cdots, t_k \in T\}$. A point $C \in \mathcal{C}_n$ is said to be *terminal* if $t(C) = C$ for all $t \in T$. It is not hard to see that $(S_1, \cdots, S_n)$ is a terminal element of $\mathcal{C}_n$ where $S_i (1 \leqq i \leqq n)$ is the elementary symmetric polynomial in $X_1, \cdots, X_n$ of degree i; in what follows it will be shown that this characterizes the terminal elements of $\mathcal{C}_n$.

The elements of R may be partially ordered by $f \leqq g \Leftrightarrow f + g = g$. For $D \in R^n$, $1 \leqq j \leqq n$, define $D^j \in R^n$ by $D_i^j = D_i(X_1, \cdots, X_{j-1}, 0, X_{j+1}, \cdots, X_n)$, $1 \leqq i \leqq n$.

Lemma 1: C is terminal $\Leftrightarrow C_1 \geqq C_2 \geqq \cdots \geqq C_n$.

Proof: Obvious.

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* By (†), $\mathcal{C}_n = \bigcup^{\infty}_{k=0} T^k(B)$; on the other hand $\mathcal{C}_n = \bigcup^{r}_{k=0} T^k(B) \Rightarrow r \geqq m$: using notation developed below, this can be proved by induction on n as follows. If $n = 1$ it is clear; assuming it is true for a given n, identify $\mathcal{C}_n$ with $\{D^{n+1} \mid D \in \mathcal{C}_{n+1}\} \subset \mathcal{C}_{n+1}$ (see remark following Lemma 3). Using the theorem below and the induction hypothesis, there is a $\mathcal{G}$ such that $\mathcal{G}(B_{n+1}) = (S_1^{n+1}, S_2^{n+1}, \cdots, S_n^{n+1}, X_{n+1})$, and $\mathcal{G}$ is a product of at least $\binom{n}{2}$ transpositions. Let $\mathcal{G}' = (1\ 2)(2\ 3) \cdots (n\ n + 1)\mathcal{G}$; then $\mathcal{G}'(B_{n+1}) = (S_1, \cdots, S_{n+1})$, $\mathcal{G}'$ is a product of $\binom{n}{2} + n = \binom{n+1}{2}$ transpositions and if for some $\mathcal{U}$ $(\mathcal{U}\mathcal{G})(B_{n+1}) = \mathcal{G}'(B_{n+1})$ then $\mathcal{U}$ must be a product of at least n transpositions.

Lemma 2: If f, $g \in R$ are such that X_i divides no summand of either, then $f + X_ih_1 = g + X_ih_2 \Rightarrow f = g$.

Proof: Writing $f + X_ih_1$ as a sum of products of X_m's, both f and g are precisely the sum of those products which are not divisible by X_i.

Lemma 3: If $D \in \mathcal{C}_n$, then for each $j = 1, \cdots, n$ there exists i such that $D_i^j = 0$.

Proof: Assume $D \in \mathcal{C}_n$ and $1 \leqq j \leqq n$. Find $t_1, \cdots, t_r \in T$ such that $tB = D$ where $t = t_rt_{r-1} \cdots t_1$. If $r = 1$, say $t = (\alpha, \beta)$, $\alpha < \beta$; if $j \neq \alpha$ then $D_j^j = 0$ and if $j = \alpha$ then $D_\beta^j = 0$. Now assume the assertion is true whenever $r < u$, and $D = t_u \cdots t_1B$. Find i such that $(t_{u-1} \cdots t_1B)_i^j = 0$ and let $t_u = (\alpha, \beta)$, $\alpha < \beta$. As above, if $i \neq \alpha$ then $D_i^j = 0$ and if $i = \alpha$ then $D_\beta^j = 0$. Induction on r completes the proof.

Given $D \in \mathcal{C}_n$, Lemma 3 provides the machinery for associating D^j in a natural way with an element $\tilde{D}^j$ of $\mathcal{C}_{n-1}$: making the initial association $X_i \to X_{i-1}$ in B_n and $i \to i - 1$ in T_n for $i > j$, define $\tilde{D}^j = t_r' \cdots t_1'B_{n-1}$ where if $t_m = (\alpha, \beta), \alpha < \beta$ then

$$t_m' = \begin{cases} t_m & \text{if} \quad (t_{m-1} \cdots t_1B_n)_i^j \neq 0 \quad \text{for} \quad i = \alpha, \beta \\ \textit{identity} \text{ otherwise} & \end{cases}$$

for $1 \leqq m \leqq r$. It is clear that $\tilde{D}^j$ represents a collapsing of D at a coordinate i where $D_i^j = 0$ plus a permutation π of the other D_i^j's: $\tilde{D}^j = (D_{\pi(1)}^j, D_{\pi(2)}^j, \cdots) \in R^{n-1}$.

However, the extent of possible permuting is limited by the completeness of the order $\leqq$ on the D_i^j's as is demonstrated in the next two lemmas which apply for $1 \leqq i, j, k \leqq n$.

Lemma 4: $D \in \mathcal{C}_n$, $D_i \leqq D_j \Rightarrow j \leqq i$.

Proof: It suffices to note that an application of a transposition to a member of $\mathcal{C}_n$ preserves the order of the indices.

Lemma 5: $D_i \leqq D_k \Rightarrow D_i^j \leqq D_k^j$.

Proof: Writing $D_i = D_i^j + X_jg$ and $D_k = D_k^j + X_jh$, obtain $D_k^j + X_jh = D_k = D_i + D_k = D_i^j + D_k^j + X_j(g + h)$ which by Lemma 2 implies that $D_k^j = D_i^j + D_k^j$, that is, $D_i^j \leqq D_k^j$.

It follows from Lemmas 1, 3, 4 and 5 that if $C \in \mathcal{C}_n$ is terminal, then $C^j = (\tilde{C}_1^j, \tilde{C}_2^j, \cdots, \tilde{C}_{n-1}^j, 0)$ and $\tilde{C}^j$ is terminal in $\mathcal{C}_{n-1}$ for $1 \leqq j \leqq n$.

Theorem: $C \in \mathcal{C}_n$ is terminal $\Leftrightarrow C_i = S_i$, $(1 \leqq i \leqq n)$.

Proof: $\Leftarrow$. This direction is clear.

$\Rightarrow$. By induction on n—if $n = 1$ then $\mathcal{C} = \{B\}$ and $B = (X_1)$ so the assertion holds. Now assume the assertion holds for $n < k$, and let $C \in \mathcal{C}_k$ be terminal. Then each $\tilde{C}^j$ is terminal in $\mathcal{C}_{k-1}$ and hence by the induction hypothesis each $C_i^j = S_i^j (i = 1, \cdots, k-1; j = 1, \cdots, k)$.

In particular then $C_i \neq X_1 X_2 \cdots X_k$ for $i = 1, \cdots, k-1$. Furthermore, each C_i can be expressed as $C_i = P_1 + \cdots + P_r$ where each P_m is a product of some but not all of the X_i's. It follows for $i < k$ that

$$C_i^j = \sum_{X_j \not| P_m} P_m, \quad \text{and consequently } C_i = \sum_{j=1}^{k} C_i^j = \sum_{j=1}^{k} S_i^j = S_i.$$

It is left to the reader to show that $C_k = S_k$ and thus complete the induction argument.

REFERENCE

1. Graham, R. L., "A Mathematical Study of a Model of Magnetic Domain Interactions," B.S.T.J., this issue, pp. 1627–1644.